BLACK SHALE AND SANDSTONE FACIES OF THE DEVONIAN "CATSKILL" CLASTIC WEDGE

IN THE SUBSURFACE OF WESTERN PENNSYLVANIA

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INTRODUCTION

Black organic-rich shales are common constituents of sedimentary sequences deposited throughout geologic time in many areas of the world. Twenty-six states in the United States and six Canadian provinces and territories are underlain by sedimentary rocks containing Devonian and Mississippian black shales (Provo, 1976). In the eastern United States, Devonian black shales are found in the Appalachian, Illinois, and Michigan basins. Natural gas has been produced from these shales for over 150 years.

Historical Review

The first well in the United States drilled specifically for natural gas produced from Devonian black shales in 1821, 38 years prior to the drilling of the historical Drake oil well. This shale gas well was drilled in Fredonia, Chautauqua County, New York, and produced enough gas to provide street lighting for the town. With that discovery, drilling commenced along the south shore of Lake Erie from Dunkirk, Chautauqua County, New York, to Sandusky, Erie County, Ohio. The gas produced from the shales was a valuable commodity available at shallow depths. The low pressure wells had relatively small open flow rates but long life spans. Drilling in the area continued throughout the 1800's and into the early 1900's, but the discovery of high flow rates from Upper Devonian sandstone reservoirs quickly put a damper on shale gas activity. There is very little information on these early shale gas wells other than some descriptive data.

In Pennsylvania the Lake Erie shale gas trend is represented by three fields, North East, Erie, and Girard (Figure 1). These fields were discovered between 1860 and 1880, and although initial production from the discovery wells was small, the fields are still productive. Ashley and Robinson (1922) reported that the wells in these fields were drilled to an average depth of 1000 feet

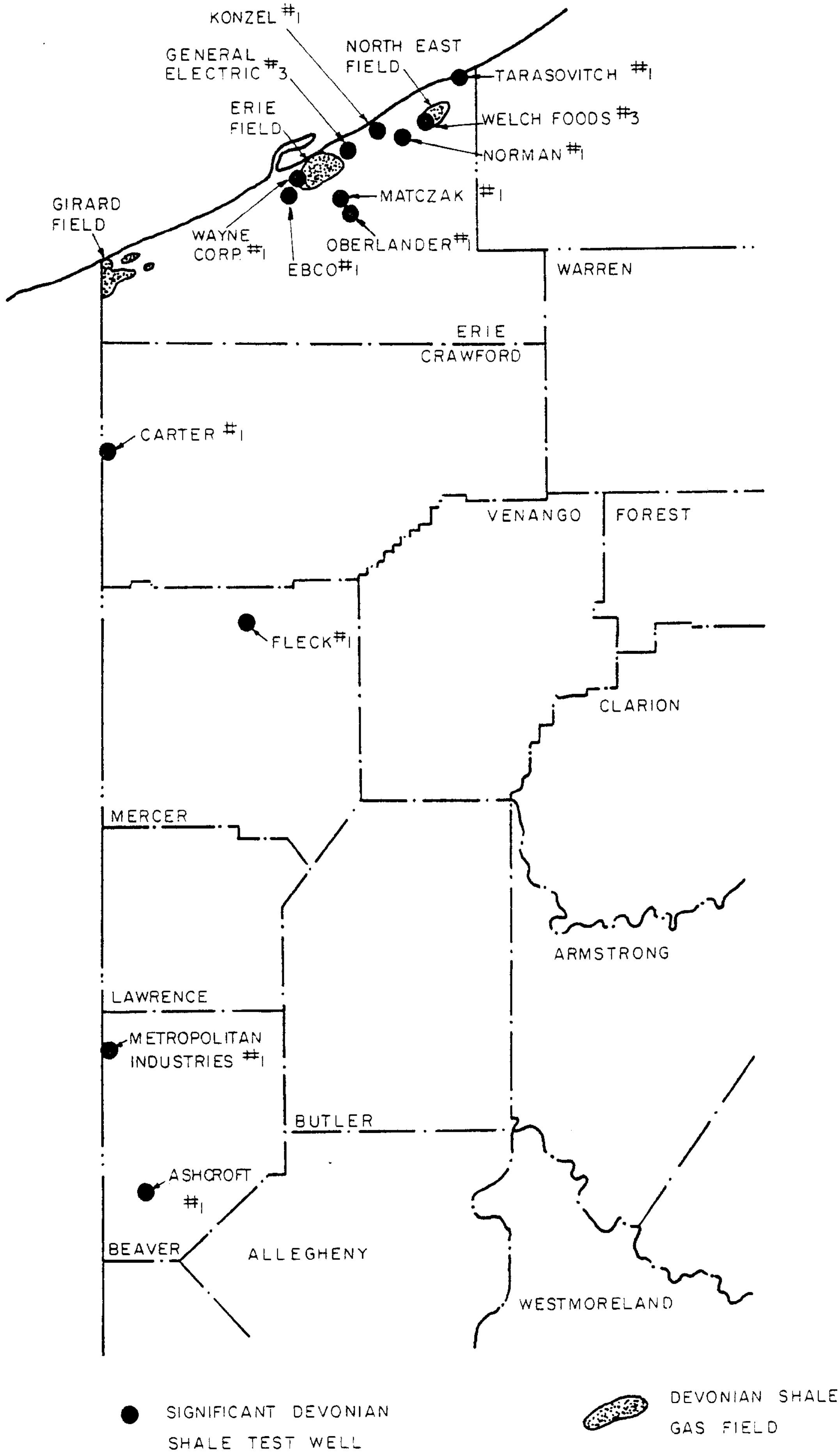

Figure 1. Locations of significant shale-gas wells and fields in Pennsylvania.

to test the Devonian Rhinestreet shale facies. There was no natural production from the shale, but after hydraulic fracturing the well initially produced 150,000 cubic feet of gas per day with a rock pressure of 1150 pounds. This flow did not last long, however, as the gas blew down after only 30 days of production. When it was shut in, the well would again build up pressure, but when opened it would quickly blow down to nothing. Piotrowski (1978) postulated that there was little natural porosity in the shale and that the gas had accumulated in fractures induced by stimulation. However, the fractures apparently were not extensive enough to constitute an adequate reservoir for commercial production of gas and the well was eventually plugged and abandoned.

In April, 1975, Frank Norman of Harbor Creek, Erie County, completed a well on his property at a depth of 875 feet in the Devonian shale. The well produced naturally at an open flow rate of 20,000 cubic feet of gas per day from three zones at 150, 400, and 700 feet; enough gas to insure an adequate domestic supply. In December, 1975, St. Joe Petroleum Corporation completed the Ashcroft #1 well in Greene Township, Beaver County. As with the nearby Metropolitan Industry well, the Ashcroft well was originally drilled as a test of a deeper formation (the Lower Silurian Medina Group) but was plugged back to test the Devonian Rhinestreet shale. Again there was no natural production, and after hydraulic fracturing there was no sustained flow. The gas was there, but with the present state of stimulation and recovery techniques it could not be produced economically. This well is currently shut in.

Nicholas Konzel of Erie, Erie County, drilled a well on his property to a depth of 900 feet. The well was completed in May, 1976, as a shale gas well with a sustained natural flow of 5,000 cubic feet of gas per day, sufficient for domestic use, from the Upper Devonian Dunkirk shale facies. In September, 1976, Moody and Associates completed the Welch Foods #3 well in the area of the old North East field as a 900 feet deep Devonian shale test. A natural open

Devonian shales.

METHODS

The Pennsylvania Geological Survey has completed nine stratigraphic cross sections of the Upper Devonian "Catskill" clastic wedge in Pennsylvania (Figure 2). These cross sections are based on gamma ray logs, with some associated sample description logs, at a vertical scale of 1 inch = 100 feet. There are three sections oriented approximately north-south and six oriented approximately east-west forming an enclosed "egg crate" shaped network.

Gamma ray logs are used as the primary source of data in this study. Almost all of the natural gamma radiation emitted from rocks is due to the radioactive potassium isotope (K^{40}) found in feldspars, micas, and other common silicate minerals, and to elements of the uranium and thorium series found in minor amounts in sediments. In sedimentary rocks the gamma ray log generally reflects shale content because there is generally a higher concentration of K^{40} in shales. Non-shaly rocks such as clean sandstones and limestones have very low levels of radioactivity and may, therefore, be differentiated from shales on a gamma ray log.

Studies of uranium-rich sedimentary rocks indicate that marine black shales have higher than normal radioactivity responses. Adams and Weaver (1958) hypothesized that this stronger gamma ray response is due to the reduction of uranyl ions in solution to tetravalent uranium ions by organic matter and other reductants. This uranium is then concentrated in the sediments by being fixed in organic complexes, adsorbed on organic material, or adsorbed on clay minerals. Many marine black shales have uranium contents greater than 10 parts per million and may approach 100 parts per million. Thus, relatively high gamma ray responses could define organic-rich shales. Sample logs used in conjunction with gamma ray logs can be used to indicate the relationship between high radioactivity and black shales. Figure 3 shows that there is a general correspondence between

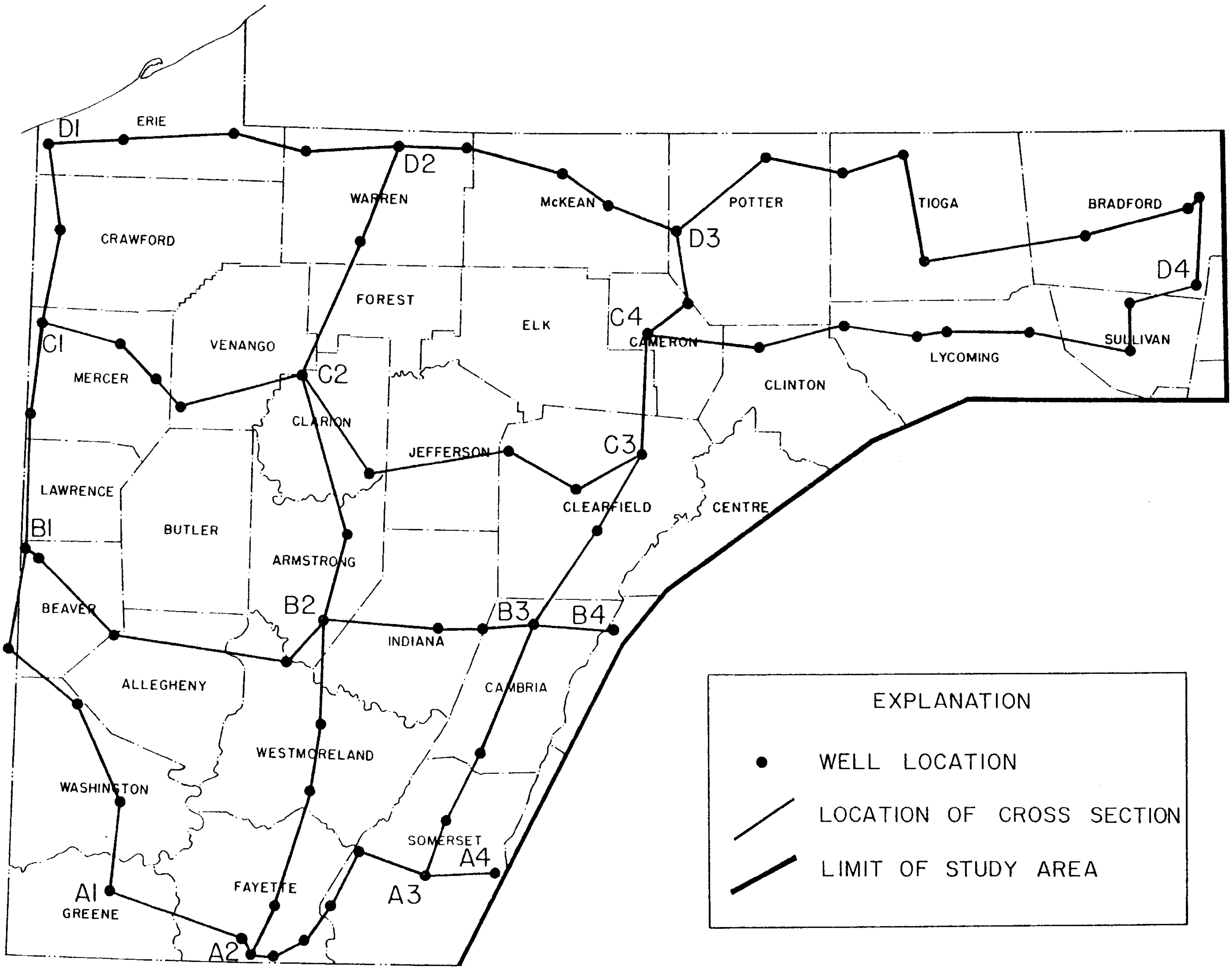

Figure 2. Index of cross sections in Pennsylvania.

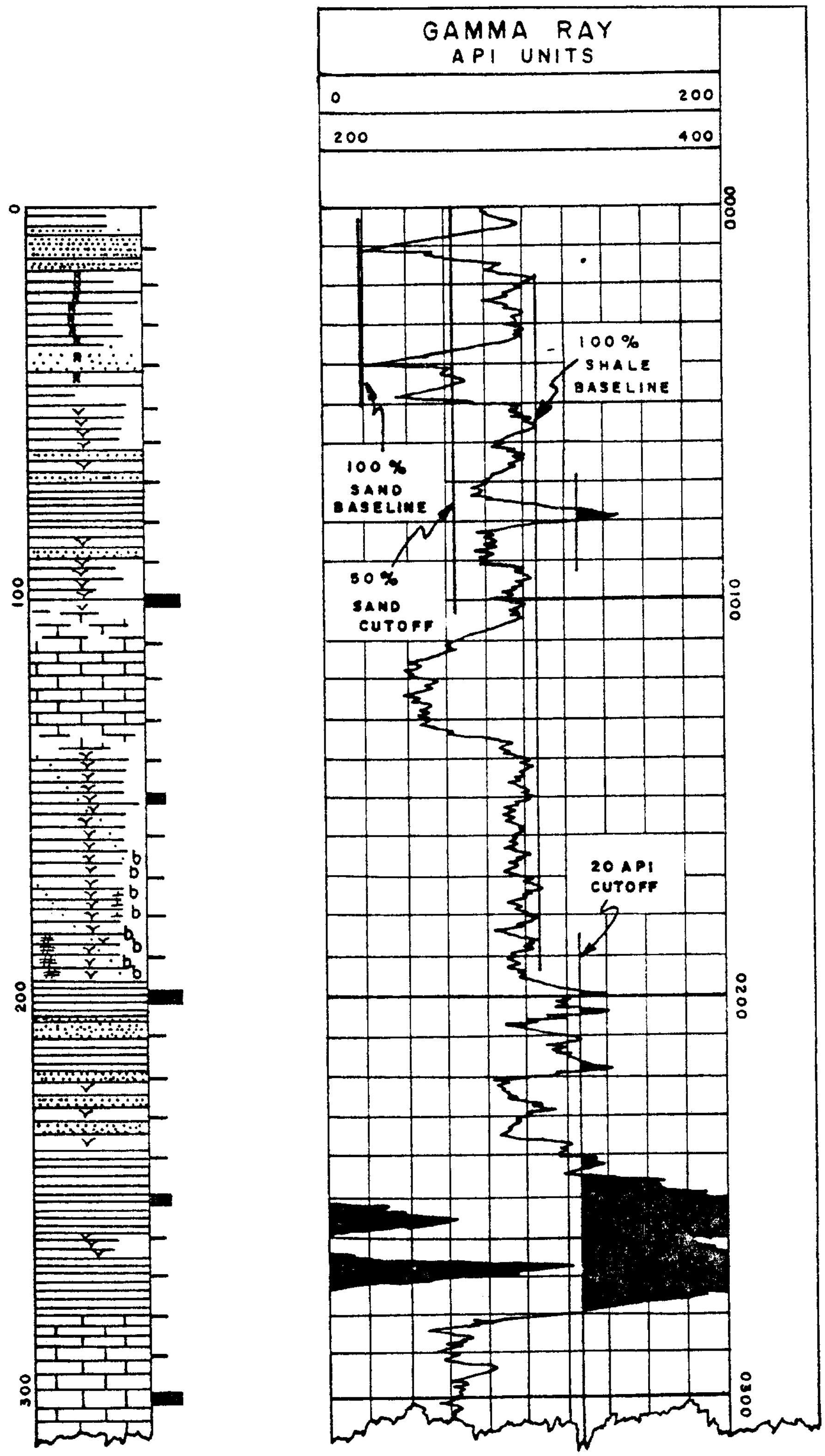

Figure 3. Portion of gamma ray and associated sample logs of a hypothetical well showing the method of determining radioactive shale and 50% clean sand cutoffs. See text for discussion.

the two types of logs, the major difference being that the sample log does not adequately define formation boundaries.

Formation density also has an important effect on gamma radiation readings. Two formations with the same amount of radioactive material but having different densities will show different radioactivity levels on the gamma ray log; the lower density rocks will be more radioactive. Gamma rays are gradually absorbed and their energies are degraded as they pass through rocks; a more dense rock will absorb more gamma rays than a less dense one. Therefore, high radioactivity responses on gamma ray logs may be due to low bulk density caused by changes in composition or fractures in the rock.

In areas where shale-gas production has been developed and studied, an empirical relationship exists between high radioactive response and gas production from shales. This has been shown by Martin and Nuckols (1976) from wells in the Cottageville Field, Jackson and Mason Counties, West Virginia, and by Bagnall and Ryan (1976) from wells in southwestern West Virginia. Martin and Nuckols plotted gas shows from 37 wells producing from Devonian shales in the Cottageville Field on a typical gamma ray log from the same area. Their diagram shows that the majority of gas production is directly related to zones having high gamma ray responses. Bagnall and Ryan analyzed well cuttings from a well in Kanawha County, West Virginia, for gas content, and directly correlated total gas content of the cuttings with high radioactivity readings on the gamma ray log from that well. Similar data have been reported by Majchszak (1978) and Smith (1978).

In Pennsylvania, the geophysical logs and production records from the Metropolitan Industry #1 well in Beaver County and the Welch Foods #3 well in Erie County were analyzed by Piotrowski, and others (1978). Details of the Metropolitan Industry well are shown in Figure 4. The various stratigraphic units and zones of perforation and production are indicated. The logs demonstrate

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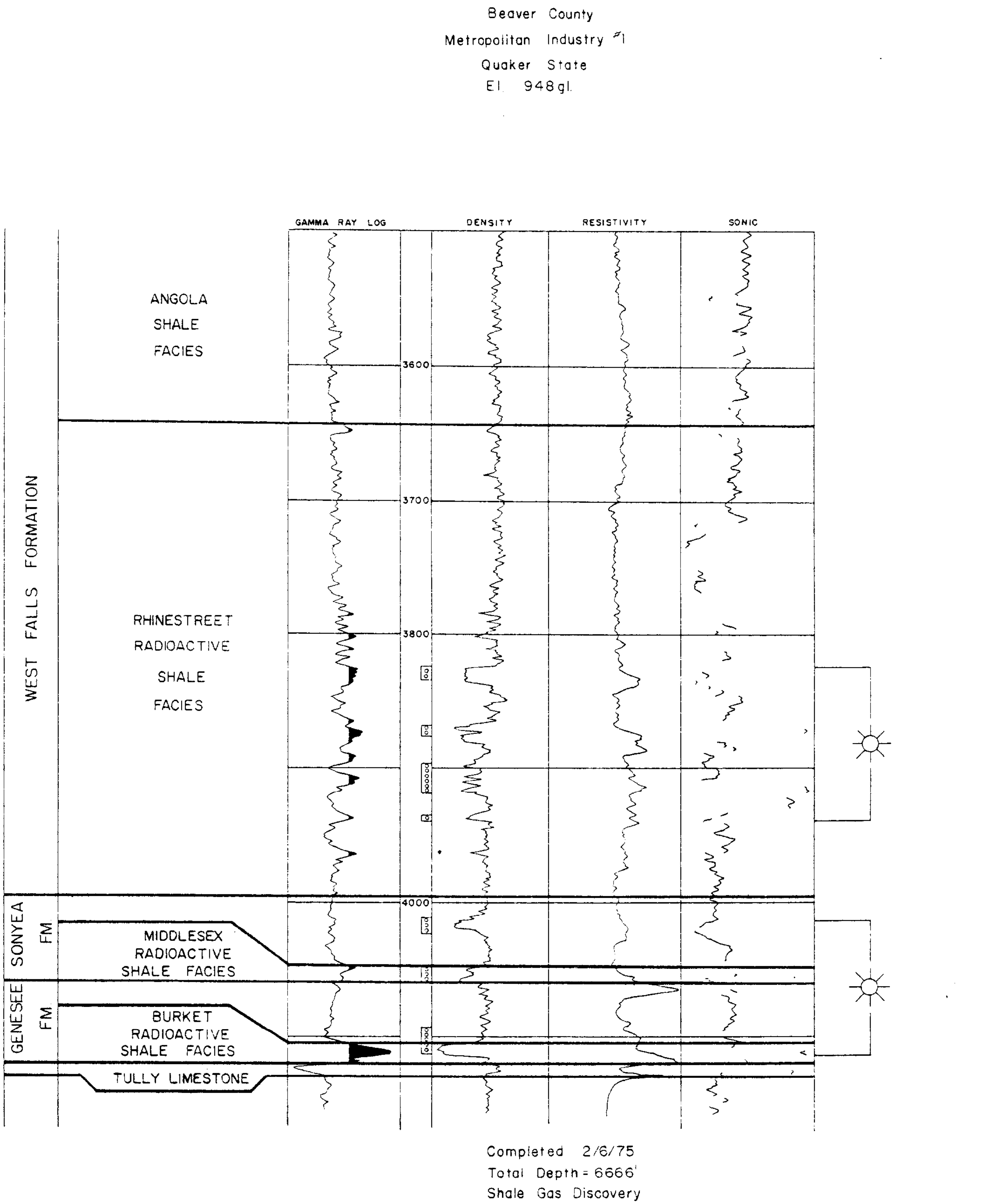

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Figure 4. Portions of combined geophysical logs of Metropolitan Industry #1 well, Beaver County, Pennsylvania, showing zones of shale-gas production.

that the productive zones correspond to high radioactivity, low density, and high porosity (the latter indicated by the neutron log). The resistivity log shows readings of 100 ohms or greater in the productive zones, probably indicating hydrocarbon content; the sonic log cycle-skips in these intervals, perhaps because of natural fractures or gas in the rock. The details of the Welch Foods well logs are shown in Figure 5. Like the Metropolitan Industry well, the Welch Foods well logs show high gamma ray response, low density, high porosity, and high resistivity associated with the gas producing horizons. A sibilation log from this well, by its positive readings, indicates that a system of fractures probably exists in the rock.

In this study, a shale having a radioactive response greater than 20 API units above a 100% shale base line (Figure 3) is considered a radioactive shale. Twenty API units was chosen as the cutoff because it is thought that this amount is consistently greater than any recognizable mechanical deviation of the logging instruments. Sands were defined on the basis of a 50% clean sand cutoff (Figure 3). A 100% sand base line was chosen by assuming that the lowest gamma ray response on the log represented a very clean sand. Knowing the 100% sand and 100% shale base lines, the 50% sand line can be chosen since the response is linear. With these cutoffs established it is easy to calculate net feet thicknesses, average sand thicknesses, and lithologic ratios.

The advantages of using gamma ray logs for this type of study are three-fold: (1) gamma ray logs are the most common geophysical log run in wells in Pennsylvania and they are usually readily available; (2) the radioactivity responses are consistent - the gamma ray log can be used effectively with fluids or casing in the hole; and (3) gamma ray logs are more accurate than sample logs because the logging equipment can give a continuous reading throughout the hole, rather than at 5, 10, or 20 foot intervals. In this way the gamma ray log can be used to pick formational boundaries within several feet, whereas sample descriptions

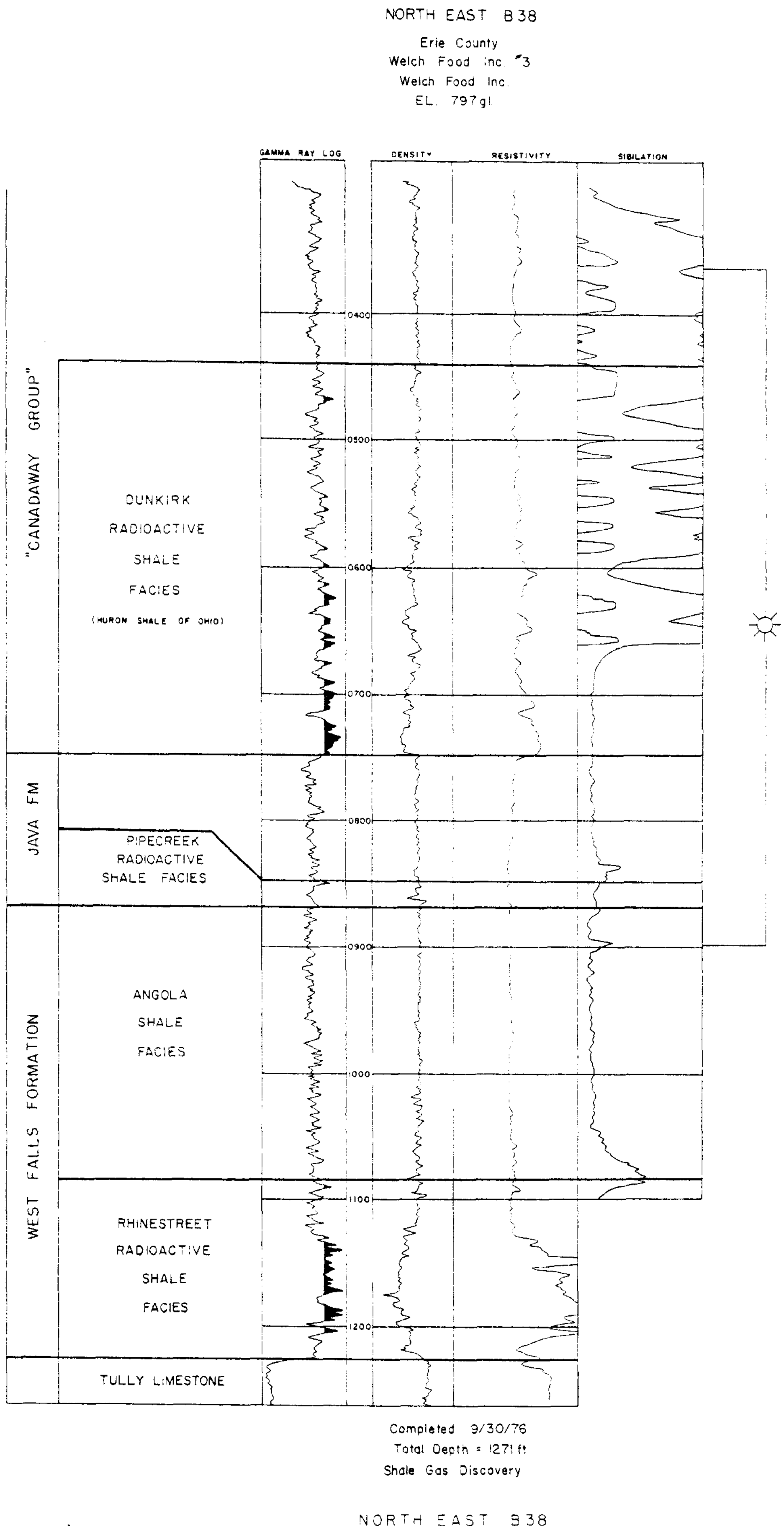


Figure 5. Portions of combined geophysical logs of Welch Foods #3 well, Erie County, Pennsylvania, showing zones of shale-gas production.

cannot.

The nine completed stratigraphic cross sections (Figure 2) form the basis of this study. The gamma ray logs from approximately 500 wells penetrating the sand and shale sections were correlated to these sections. Logs were chosen so that there would be, where available, at least one data point per five minutes of latitude and longitude throughout the study area. Each log has a designated file number indicating 15-minute quadrangle, reference section, and number as set up by the Pennsylvania Geological Survey Oil and Gas Geology Division (Kelley and Wagner, 1970). Each 15-minute quadrangle is divided into nine 5-minute sections labeled A to I. Therefore, a log labeled Erie B-128 indicates that it is from the 128th well of record in the Erie 15-minute quadrangle and that it is located in section B of that 15-minute quadrangle.

GENERAL STRATIGRAPHY

The black, organic-rich shales of Devonian age in Pennsylvania occur at and near the base of a thick, wedge-shaped sequence of sedimentary rocks known in western Pennsylvania by drillers as the "Catskill" clastic wedge. This westward-thinning, bevel-edged, sequence of intercalated marine, transitional, and continental facies attains a thickness of over 7,000 feet in south central Pennsylvania and thins to about 2,000 feet in the northwestern part of the state. The rocks are most commonly shales, siltstones, sandstones, and red beds, but a few thick limestones are found in the lower part of the sequence.

The stratigraphic terminology for the Upper Devonian sedimentary sequence in the subsurface of Pennsylvania is confused by contradictions, unit names defined by non-standard procedures, and drillers' units to which conflicting names have been applied. Names such as "Catskill", "Chemung", and "Portage" have been used in a wide variety of ways (see Frakes, 1963, for an excellent discussion of this problem) and it seems that only those units which have been described from outcrop localities in central Pennsylvania have any acceptable status. This paper is, in part, an attempt to initiate a more consistent and more meaningful stratigraphic nomenclature for the subsurface Upper Devonian of Pennsylvania. The old nomenclature is, if anything, overdeveloped. Most of the terminology used in the black shale portion of this study is based on that of the New York Geological Survey (Rickard, 1975) modified by the U. S. Geological Survey (Oliver, and others, 1969). No attempt has been made to define all of the Upper and Middle Devonian formation members recognized in New York. Fortunately, most of the formational boundaries are based on marker horizons such as limestones and black shales which are readily distinguishable in the subsurface by their gamma ray responses.

Black Shale Facies

Three major and three minor black shale facies are recognized in the subsurface of Pennsylvania. The major units include the Middle Devonian Marcellus facies of the Hamilton Group, and the Upper Devonian Rhinestreet facies of the West Falls Formation and Dunkirk facies of the "Canadaway Group". The minor units are the Burket facies of the Genesee Formation, the Middlesex facies of the Sonyea Formation, and the Pipe Creek facies of the Java Formation, all Upper Devonian. These black shale facies in Pennsylvania and their relationship to the formally recognized units of New York and Ohio are shown in Figure 6.

At its thinnest the Marcellus facies in the subsurface of Pennsylvania may be equivalent to a portion of the Marcellus Formation of New York, whereas it probably encompasses the total Marcellus and Skaneateles formations and part of the Ludlowville Formation in the area of its greatest accumulation. The Burket facies of the Genesee Formation is equivalent to the Geneseo Shale Member of New York. In the northeastern portion of the study area, the Burket is split into an upper "Renwick" black shale and a lower "Geneseo" black shale separated by non-black shales and siltstones. Geneseo as used by the New York Geological Survey is applied to the lower unit regardless of the presence or absence of the

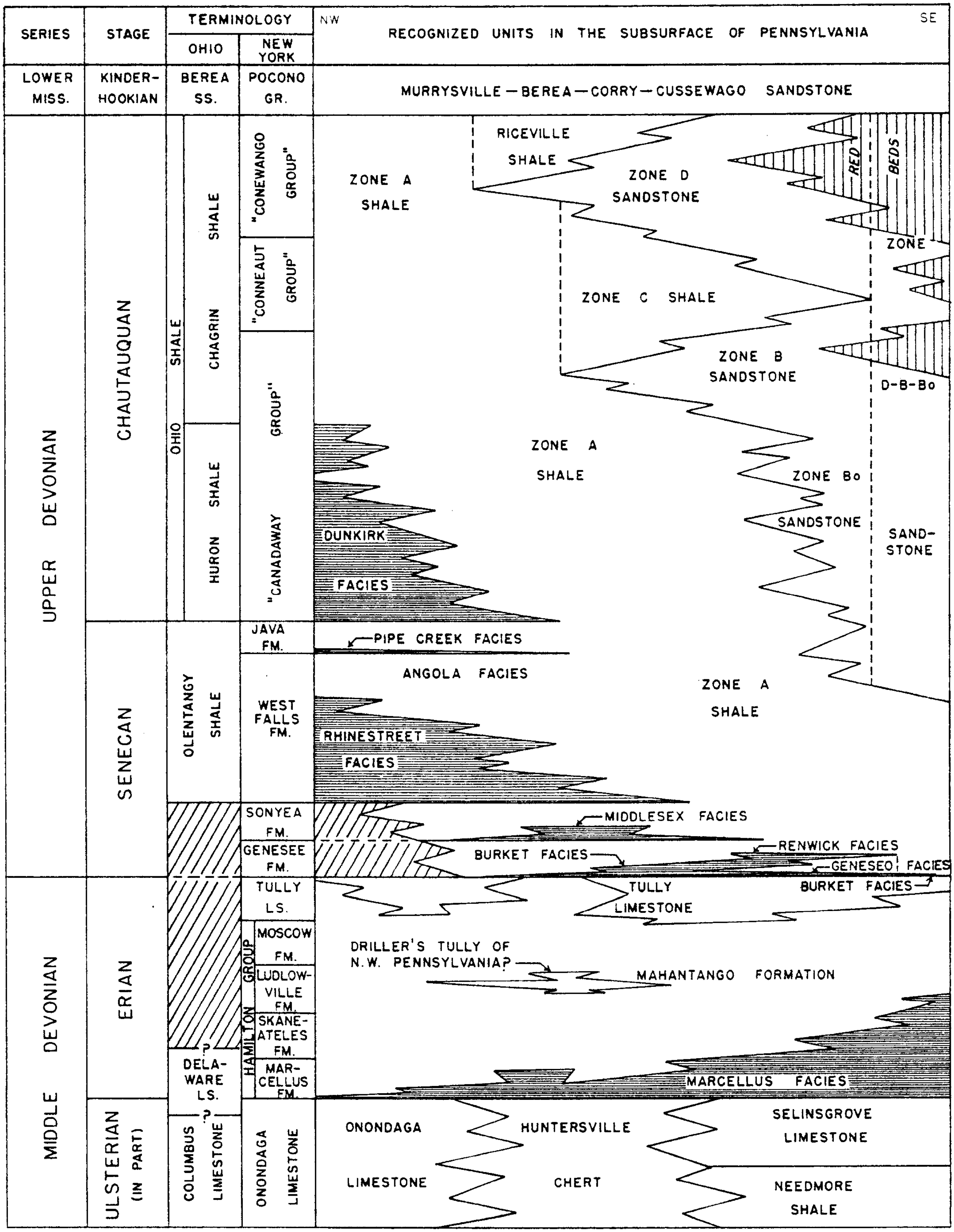


Figure 6. Schematic illustration of Upper and Middle Devonian stratigraphic units in the subsurface of Pennsylvania and correlation with Ohio and New York stratigraphic section (after Oliver, et al., 1969, and Patchen, 1977).

Renwick.

The Middlesex facies of the Sonyea Formation in the Pennsylvania subsurface is equivalent to the Middlesex Shale Member of New York, and the Rhinestreet facies of the West Falls Formation corresponds to the Rhinestreet Shale Member of New York usage. The Pipe Creek facies of the Java Formation is a very thin but very persistent black shale recognized at the surface in New York. The Middlesex, Rhinestreet, and Pipe Creek facies are individual units in Pennsylvania and New York, but they coalesce westward and in Ohio are recognized as a single unit, the Upper Olentangy Shale. The black shale identified in the subsurface of Pennsylvania as the Dunkirk facies of the "Canadaway Group" is equivalent to the Dunkirk Shale Member of New York plus a number of superjacent members of the "Canadaway" in those areas of the Dunkirk's greatest accumulation. The Dunkirk, like the Middlesex, Rhinestreet, and Pipe Creek facies, thickens westward from New York through Pennsylvania and into Ohio where it is several hundreds of feet thick and is recognized by the name Huron Member of the Ohio Shale.

Sand Facies

The Upper Devonian shallow sand oil and gas reservoirs have been the subject of a confusing terminology, originating mostly from drillers who were less interested in the geological consistency and usefulness of stratigraphic nomenclature than they were in the amount of oil and gas produced from a reservoir. Names were liberally applied to sandstones and conglomerates at many localities of first discovery and these names were carried over long distances where they were commonly applied to non-equivalent sands. Certain of the sands appear to be continuous, but gamma ray correlations indicate that the majority of drillers terms define belts of sand and silt lenses, rather than individually mappable units. In an attempt to create some order out of the chaos, Kelley and Wagner (1970) defined a number of zones which represent "bundles" of drillers' "sands".

AGE	ZONES	UNITS	SAND NAMES
MISSIS-SIPPIAN		Big Injun	Loyalhanna Big Injun-Mountain Burgoon
	MIDDLE AND LOWER POCONO		Shenango, Slippery Rock, Squaw Second Gas Berea, Cussewago, Corry, Knapp, Murrysville
?	RICEVILLE		Riceville Shale in north central Pennsylvania
UPPER DEVONIAN	D UPPER SAND ZONE	D 3	Venango First, Hundred Foot, Fifty Foot, Gantz, Drake, Tuna Red Valley, Lytle, Rosenberry, White, Salamanca
		D 2	Venango Second, Salt, Upper Nineveh, Lower Nineveh, Snee, Shira, Boulder Venango Third Stray, Venango Third, Venango Fourth (Fourth), Venango Fifth (Fifth), Venango Sixth (Sixth), Grey, Black, Green, Gordon Stray, Gordon, McDonald Fourth, McDonald Fifth, Knox Third Stray, Knox Third, Knox Fourth, Knox Fifth, Wolf Creek, Clarion, Byram, Conewango, LeBoef, Magee Hollow
		D 1	Bayard Elizabeth
	C SHALE ZONE		
	B MIDDLE SAND ZONE	B 4	Warren First Warren Second Queen Glade, Bradford First, Eighty Foot, Clarendon Stray
		B 3	Clarendon, Sugar Run, Watsonville, Dew Drop, Chipmunk, Cherry Grove, Gartland, Upper Balltown, Lower Balltown, Speechley
		B 2	Tiona, Cooper Stray, Cooper Bradford Second Klondike, Harrisburg Run Deerlick, Sliverville
		B 1	Bradford Third Lewis Run Upper Kane Lower Kane Sartwell
	Bo LOWER SAND ZONE	Undivided	Haskill, Reily, Elk Humphrey, Benson, Alexander

Figure 7. Generalized stratigraphic column of producing sandstones in the Upper Devonian of western Pennsylvania. Placement of sand names within a zone refers only to the position of the sand in the area where it was first named or used.

We have accepted their zonation with modification (Figures 6 and 7). In this study, Zones D, B, and Bo represent three identifiable "bundles" of sands which are further subdivided on the basis of the drillers' terminology, while Zones A and C are shale facies. The zones are believed to be correlatable lithologic divisions which may be formally named in the future.

Zone A is a very general division. It represents all of the non-black shales and shaly siltstones which lie above the top of the highest definable black shale facies and below the base of the lowest identifiable sand (Figure 6). In Erie County where the shallow sands are absent, Zone A includes all of the sedimentary rocks from the top of the Dunkirk facies to the base of the overlying Mississippian rocks (or to the surface in areas where the Mississippian has been eroded). In Somerset County, however, Zone A encompasses all of the sediments lying between the top of the Burket facies and the base of sandstone Zone Bo. Zone C and the Riceville Shale (Figure 6) are tongues of Zone A which are intercalated with the sandstone "bundles" of Zones D and B and the basal sandstones of the Mississippian Pocono Group.

The unit designations B1, B2, B3, B4, and D1, D2, D3 within lithic Zones B and D (Figure 7) are <u>interval</u> divisions rather than lithologic division. This is done in an attempt to show the relationship between drillers' terminology and stratigraphic units. These divisions are based on the positions of the known producing "sands" (belts of discontinuous and non-correlatable sandstone lenses) as first named by oil and gas drillers. Placement of the sand within each unit designation refers only to the position of that sand in the area where it was first named. Zones D and B are separated by the shale Zone C. In the areas where it is less than 50 feet thick, Zone C cannot adequately be differentiated from the interbedded shales within the sand zones. At this point Zones B and D coalesce and, with Zone Bo, become a single sandstone Zone D-B-Bo (Figure 6). Zone Bo is best developed in the eastern portion of the study area where sandstones and siltstones develop below the limit of Zone B as recognized elsewhere.

DISCUSSION OF THE MAPS

General

This portion of the report attempts to describe the import of the structural, isopach, and lithofacies data presented in the accompanying 39 maps. Twenty-two of these maps are based on the Upper and Middle Devonian radioactive black shales and their associated lithologies. The remaining 17 maps deal with the Upper Devonian sandstone zones and intercalated shale zones. Interpretation of these maps is based not only on the maps themselves, but also on individual gamma ray logs and numerous cross sections prepared during the mapping phase of the study.

Black Shale Maps

A. Total Interval from Top of Devonian to Base of Marcellus

The total interval from the Mississippian-Devonian boundary to the base of the Marcellus shale facies exhibits the pattern of southeastward thickening (Plate 1) which is characteristic of most of the individual units within it. Major changes in the gradual basinward thickening of these units are rare. The map of the net feet of radioactive black shale in the total interval (Plate 2) shows a linear pattern of thick and thin areas which seem to be related to the general northeast-southwest strike of the Appalachian structures. This map is a composite of all of the radioactive shale facies and it shows, in general, the trends associated with them. It especially depicts the three major shale belts in Pennsylvania. The Marcellus belt in the eastern portion of the study area is represented by the isolated thick areas of 150 net feet or greater in the southeast and the broad continuous pattern of greater than 150 net feet thickness in the northeast. The Rhinestreet and Dunkirk belts are represented by the northwestern trends of 150 net feet or greater thickness, with the Dunkirk belt occupying the

Lake Erie margin and the Rhinestreet belt lying somewhat to the southeast of it on a line from Beaver to Warren Counties. The small, isolated thick area in McKean County is the result of local thickening of organic-rich shale.

B. Middle Devonian

1. Hamilton Group

The Hamilton Group in the subsurface of Pennsylvania is divided into the lower Marcellus shale facies and the superjacent Mahantango Formation which is equivalent to the Skaneateles, Ludlowville, and Moscow formations of New York (Figure 6). The Hamilton Group isopach map (Plate 3) indicates the general thickening trend shown in Plate 1. However, it should be noted that there is a slight change in the spacing of the contour lines at approximately the 500 foot line. To the southeast, especially in the center of the study area, the contours are more closely spaced, while to the northwest they open up. The isolated 500 foot contour in central McKean County is the result of a single well in which the Onondaga equivalent sediments are radioactive black shales, adding about 100 feet to the lower portion of the Hamilton Group.

The Map of net feet of radioactive black shale in the Hamilton Group (Plate 4) shows the eastern belt of black shales delineated in Plate 2. Using an arbitrary 125 net feet of shale as a cutoff between low and high values, the Marcellus develops into a series of linear thickened areas paralleling the structural axes. Comparison of this map with that of the structure on top of the Onondaga Group (Plate 5) indicates that the majority of these thickened areas are developed on the crests of anticlines. Harper and Piotrowski (1978) proposed that the structures in this area were probably active tectonic features throughout much of the Devonian. The anticlines, therefore, would have been positive features at the time of deposition of the Marcellus black shale. Stagnant, anaerobic conditions could then occur within the organic-rich sediments accumulating on these features if current activity were restricted to the low areas between the crests. These currents would serve the double purpose of aerating and winnowing the sediments in the troughs, and isolating patches of anaerobic conditions on the anticlines. We hope to study this problem in the future to determine if, in fact, this is a valid hypothesis for the origin of the linear thickness highs.

The near coincident patterns of the Marcellus facies map and of the Onondaga structure map indicate a change in Marcellus facies thickness and structural complexity along the same line between Greene and Potter Counties. This correlates with the change in contour interval of Hamilton thickness as previously stated.

2. Tully Limestone

The Tully Limestone isopach map (Plate 6) corresponds well with the previously published map of Jones and Cate (1957, Plate 6). We have added some modifications, but it is significant to note the similarities between the older map interpreted from well-cutting data and our Plate 6 interpreted from gamma ray logs. We agree with Jones and Cate that the Tully Limestone occurs, and indeed thickens, in northwestern Pennsylvania, contrary to the ideas presented by Heckel (1969, 1973) and Wright (1973) and repeated by other authors (for example, Dennison and Head, 1975). Areas where the limestone is absent occur in the western part of Lawrence and Mercer Counties and in portions of Warren and McKean Counties, but we can find no reason for calling the thick Middle Devonian carbonates in Venango, Crawford and Erie Counties anything but Tully. We have examined a correlated section of gamma ray logs extending up-dip from the known

Tully outcrop in central Pennsylvania to the subsurface of Erie County (Louis Heyman, unpublished cross section, 1978) and see no evidence for the unconformity usually indicated in place of the Tully (Wright, 1973; also Wallace, and others, 1977; and Roen, and others, 1978).

A linear area of thick Tully, extending from Fayette County into Westmoreland County, lies along the crest of the Chestnut Ridge anticline. To the east of this area, the Tully becomes less calcareous and eventually disappears as a limestone along a line corresponding to the crest of the Laurel Hill anticline. The Tully is not eroded here, but has undergone a lateral change from a carbonate to a calcareous shale. We surmise from this that the Laurel Hill anticline was an active positive feature which became an effective shield against clastic influx from the southeast by slowing water movement over it. On the crest and to the east of this structure, carbonate deposits were diluted with fine-grained clastics which were no longer carried in suspension. On the west side of the anticline, carbonate deposition was essentially undiluted by clastic influx. The Chestnut Ridge anticline may also have been positive and, if the water depth over these two structures was shallow enough, thicker accumulations of carbonates would be deposited on a postulated "Chestnut Ridge carbonate platform" accounting for the pattern seen on the map.

Another thick area of Tully Limestone occurs along the Allegheny-Westmoreland County boundary and extends northeastward. We have no immediate explanation of this feature.

The Tully Limestone is relatively thick in the southeast and thins to the northwest. This change occurs where structural changes occur, along a line from Greene County to Potter County (Plate 7). The structure on the top of the Tully is essentially the same as that on the top of the

Onondaga Group (Plate 5) indicating that there was little apparent tectonic activity during the Middle Devonian.

C. Upper Devonian

The isopach of total Upper Devonian shale (Plate 8) reflects the distribution of shale from the top of the Tully Limestone, or its equivalent, to the base of the first sand (shale Zone C and the Riceville Shale are not included). In northwestern Pennsylvania, the shale is relatively thin (less than 3,000 feet) due to the general thinness of the total section. In the central portion of the study area, the alternating thin and thick belts are apparently partially related to the distribution of Zone B Sandstone (see Plate 27). The easternmost belt of thin shale lies along the area in which the Zone Bo and Zone B sands (Plates 25 and 27 respectively) are best developed.

The total net feet thickness of radioactive black shales in this interval (Plate 9) shows that the thickest Upper Devonian black shale is found in northwestern Pennsylvania. This distribution of greater than 100 net feet of shale is due in most part of the presence of the Dunkirk and Rhinestreet facies.

1. Genesee Formation

The Genesee Formation, like the Hamilton Group, gradually thickens toward the southeast. In extreme northwestern Pennsylvania the Genesee Formation is missing, apparently having been pinched out or eroded from the area. A noticeable change in rate of thickening occurs at about the 100 foot contour line (Plate 10). To the east, the superjacent Middlesex radioactive shale facies of the Sonyea Formation changes character by dilution of the organic-rich shale with non-organic clastics. Where it disappears the Genesee Formation can no longer be defined.

However, the individual radioactive shale members within the Genesee can still be distinguished.

The Burket radioactive shale facies is identifiable throughout most of the study area, although it pinches out in northwestern Pennsylvania (Plate 11). To the east, the Burket thickens gradually until, in the central portion of the study area, thickening becomes more rapid. At about the 50 foot contour line the Burket splits to become the upper Renwick facies and the lower Geneseo facies (Figure 6) separated by unnamed non-radioactive shales and siltstones. The distribution of these rocks is quite different from the distribution of other units in the Devonian of Pennsylvania. The Burket-Geneseo-Renwick interval attains its maximum development in the northeastern, rather than south-eastern portion of the study area, implying a radically different source area for the organic-rich clastics. This is also implied by the net feet of radioactive shale from this interval (Plate 12) which has its maximum distribution in the northeast. While most of the Upper and Middle Devonian clastic input was from the southeast, the lower Genesee members were apparently formed by a shift in the center of deposition to the northeast, with provenance from what is now New York State.

2. Sonyea Formation

The Sonyea Formation thickens to the southeast (Plate 13) in a manner similar to that of the Hamilton Group and the Genesee Formation. In extreme northwestern Pennsylvania the Sonyea, like the Genesee, is absent. The superjacent Rhinestreet radioactive shale facies of the West Falls Formation is absent in the central portion of the study area, but a distinctive marker at the base of the Rhinestreet persists further toward the southeast. Where the Rhinestreet marker can no longer be picked, the Sonyea Formation can no longer be recognized as a mappable lithologic unit. The lower member of the Sonyea, the Middlesex radioactive shale facies, can be traced only a little farther east before it too dies out (Plate 14).

The Middlesex is rarely identified in the subsurface of Pennsylvania as a thick radioactive shale unit, although Sutton (1963) noted that it is approximately 160 feet thick in south central New York along the Pennsylvania-New York border. Although the Middlesex facies may be over 100 feet thick in some areas of Pennsylvania, only in McKean and Potter Counties does it attain a thickness of greater than 25 net feet of radioactive shale (Plate 14). This distribution is similar to the Burket-Geneseo-Renwick facies distribution.

The structure contour map on the base of the Middlesex shale (Plate 15) shows that the shale has a gentle southeasterly dip northwest of the area of major structures in the subsurface. Here, the base of the Middlesex becomes structurally more complex, forming an asymmetrical syncline with a gentle western slope and a contorted and more steeply dipping eastern slope. Unfortunately, the Middlesex radioactive shale becomes diluted and thereby unidentifiable from other clastics in this eastern area so that the structural picture on the eastern side of the study area is obscured.

3. West Falls Formation

The West Falls Formation gradually thickens to the southeast (Plate 16). It can no longer be identified, however, where the superjacent Pipe Creek radioactive shale facies of the Java Formation disappears. The limit of the West Falls occurs in the central portion of the study area.

The Rhinestreet radioactive shale facies is identifiable to about the center of the study area, but a Rhinestreet "marker" which extends farther to the southeast can be distinguished on gamma ray logs. This marker cannot be considered as part of the measurable facies thickness because it does not contain any radioactive shale, using the accepted definition of the 20 API unit cutoff. The net feet distribution of Rhinestreet shale in Pennsylvania (Plate 17) indicates that the Rhinestreet is most well developed in a northeasterly striking belt extending from Beaver and Lawrence Counties to Warren and Erie Counties. It is confined to the northwest portion of the state (northwest of a line between Greene and Potter Counties), whereas the Marcellus facies of the Hamilton Group is most well developed to the southeast of this line (Plate 4).

The structure on the base of the Rhinestreet facies and marker (Plate 18) is quite similar to that of the Middlesex. The base of the shale dips gently to the southeast as far as the line from Greene County to Potter County at which point the structure becomes somewhat more complex, forming a syncline. The Rhinestreet marker can no longer be identified in the eastern portion of the study area, and this obscures the structural picture in this area.

4. Java Formation

The Java Formation thickens gradually to the southeast, but quickly becomes unidentifiable where its upper boundary, the Dunkirk radioactive shale facies of the "Canadaway Group", can no longer be recognized (Plate 19). Because the radioactive shales of the Java Formation never achieve a net feet thickness greater than 20 feet, we have not included a map of this distribution. The structure on the base of the Pipe Creek radioactive shale facies (Plate 20) indicates that it dips gently to the southeast, at least as far as the limit of the radioactive shale.

5. Dunkirk Radioactive Shale Facies

The Dunkirk radioactive shale facies is the basal member of a group of rocks traditionally referred to as the "Canadaway Group". However, we cannot recognize the "Canadaway Group" in the subsurface of Pennsylvania because its upper boundary cannot be picked on a gamma ray log. This boundary is considered by Tesmer (1963) to be marked by the first appearance of gray siltstones containing distinctive fossils characteristic of the superjacent "Conneaut Group". By this definition the contact is a biostratigraphic, rather than a lithostratigraphic, boundary. Therefore, the "Canadaway Group" by Tesmer's definition, is not based on any mappable lithologic units and cannot stand as a lithostratigraphic entity. Rickard (1975) places the contact between the "Canadaway" and "Conneaut" groups as the base of the Dexterville Formation which, according to Tesmer, is not lithologically distinct from subjacent rocks. The U. S. Geological Survey does not use the name "Canadaway Group", preferring instead to use individual formation and member names (Oliver, and others, 1969). The Dunkirk, according to this preference, is the basal member of the Perrysburg Formation which has as its upper boundary the Laona Sandstone. Unfortunately, we have been unable to trace the Laona very far in Pennsylvania. It appears to be one of the sand and silt lenses of Zone B or Zone Bo which grades laterally into siltstones and shales indistinguishable from surrounding sediments in northwestern Pennsylvania. We have retained the name "Canadaway" here only for the sake of simplicity realizing that its history is filled with nomenclatural confusion.

The Dunkirk radioactive shale facies is limited in its distribution to the northwestern part of Pennsylvania. The greatest net feet thickness of radioactive shale (Plate 21) in this facies is restricted to

Erie County essentially paralleling the margin of Lake Erie with a prominent north-south thick tongue, which almost exactly coincides with the thick "Tully Peninsula" (Plate 6) and with the area of the thickest accumulation of Rhinestreet facies (Plate 17). The structure on the base of the Dunkirk (Plate 22) dips gently to the southeast.

Sand Maps

The Upper Devonian sandstones are generally distributed as bar-like and channel-like lenses in the subsurface of Pennsylvania. Some of the sandstones and siltstones of Zone Bo are believed to be turbidites. The bar and channel patterns of sand distribution also show up in the isopach maps and maps of net feet of sand of the individual zones and their subdivisions (Plates 23-32, 34-38). Differences in distribution of the sand appear to be due mostly to transgressive and regressive phases of the Devonian seas.

The three sand zones (Figure 6) represent successively more westward progradational phases of the Upper Devonian "Catskill" clastic wedge. Zone Bo is restricted to the eastern part of the study area (Plate 25), Zone B is generally limited to the east of longitude 80° W (Plate 27), and Zone D almost extends into Ohio (Plate 34). The sands of Zone Bo may be mostly turbidites as suggested by their gamma ray log responses (sharp basal contacts and gradational upper contacts; and log indications of "dirty" sands), and the general geometry of the zone in terms of net feet of sand (Plate 26). We believe that at least a portion of Zone Bo can be correlated with the Benson sands of West Virginia, sediments which have been shown to be turbidite deposits (Cheema, and others, 1977). These sands are probably equivalent in part to the Dunkirk radioactive shale facies in northwestern Pennsylvania (Figure 6) and may be equivalent to other lower black shale facies which die out in the western part of the state.

Zone B Sandstone contains the Glade, Speechley, Balltown, and Bradford Third sands of drillers' terminology among others (Figure 7), all of which are highly productive gas and oil reservoirs in the northern part of the study area and to a limited extent in the south. The Speechley is the most widespread sand belt in Zone B. It may be a fairly continuous sand, but unpublished studies of the Speechley (W. R. Wagner, personal communication, 1974) suggest that it is more likely an anastomosing series of coalesced channel or bar-finger sands. The isopach and net feet of sand maps of Zone B (Plates 27-32) indicate that most of the sands were deposited in channel and bar patterns, while distribution of red beds in this interval (the red beds of Zone B are restricted to the eastern portion of the study area) suggests that the majority of Zone B sand was deposited under marine conditions.

The isopach map of Zone C shale (Plate 33) is interesting in that it shows the same general sort of patterns as the sand maps, with the shale increasing toward the west. The zero contour line coincides with the limit of the individual sand zones, for it is along this line that the Zone D and B sands coalesce. The western limit of Zone C shale is defined by the disappearance of Zone B (Figure 6).

Zone D Sandstone, containing among others the Hundred Foot, Venango, Gordon, and Bayard sands of drillers' terminology, is a combination of bar and channel patterns (Plates 34-38), more so than the Zone B sandstone. Zone D2 (Plate 37) represents the farthest westward extent of coarse clastics in the Upper Devonian. Most of the wells examined in this study penetrated red beds as well as sands in Zone D2 indicating that the "Catskill" facies of continental sediments also had its farthest westward extent in this interval. These sands are probably very near-shore marine and non-marine sediments. Zone D2 continues to maintain its interval thickness in the east, but the net feet of sand map (Plate 37) shows that the sands within the interval become less developed and eventually lost. The shales and siltstones which replace the sands in this section are mostly red or reddish-brown in color, another indication of the continental facies progradation.

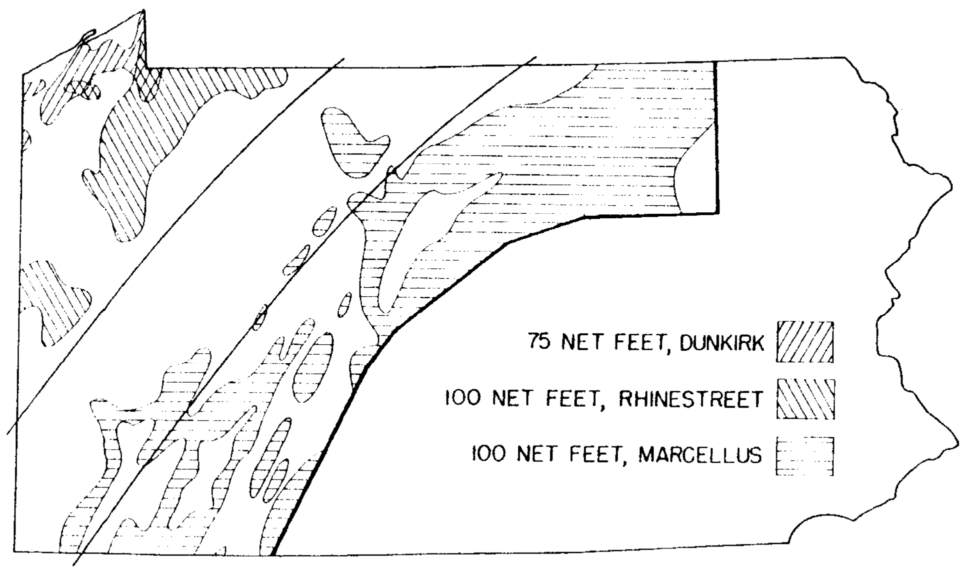
The Riceville shale is the last effort of the Devonian seas to transgress onto the near-shore marine and continental facies of Zone D. The distribution of the Riceville shale is restricted (Plate 39). It is intercalated with Zone D and the basal Mississippian sandstones approximately along a line between Greene County and Potter County.

General Stratigraphic Observations

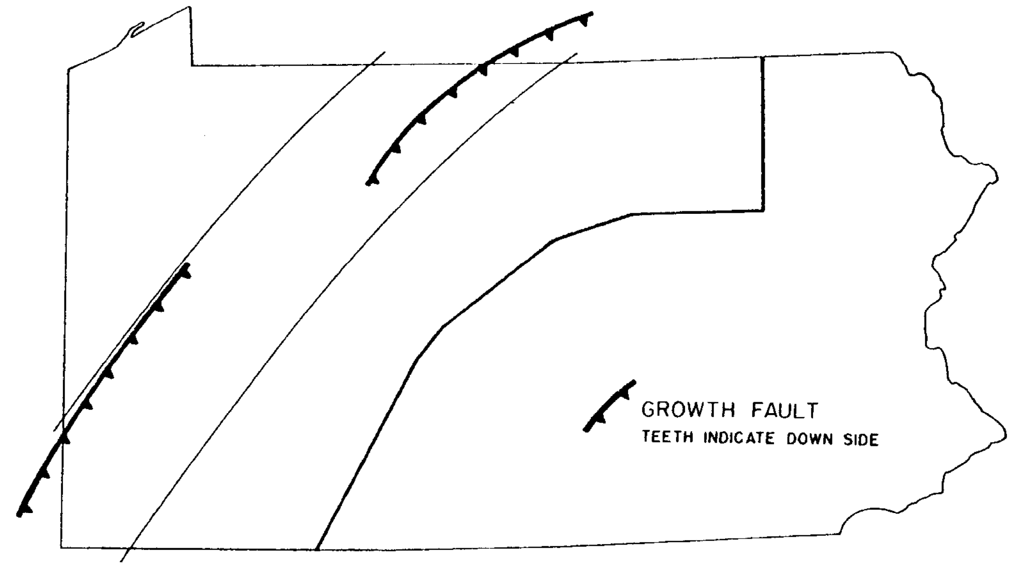
During the course of mapping, it became apparent that there was evidence of a geological feature associated with, and possibly controlling, the distribution, thickness, structural trends, and facies variability of the Middle and Upper Devonian rocks in the subsurface of western Pennsylvania. This phenomenon is expressed in many of the maps as a broad zone extending from Greene County in the southwest to McKean and Potter Counties in the northeast, parallel to the major structural trend of the Valley and Ridge Province in central Pennsylvania. We noticed that the Dunkirk and Rhinestreet facies limits lay along the approximate boundaries of this zone (Plates 17 and 21) and could, therefore, be used to delineate it. Other features related to this zone include: change in the contour interval of the Hamilton Group isopach map (Plate 3); restriction of the thickest accumulation of the Marcellus facies to the eastern portion of the study area (Plate 4); distribution of the Tully Limestone (Plate 6); isopach of the total Upper Devonian shale (Plate 8); total net feet of radioactive shale in the Upper Devonian (Plate 9); isopachs of the West Falls Formation (Plate 16) and Java Formation (Plate 19); structure on the various units (Plates 5, 7 and 18 especially); and isopachs of the Zone Bo Sandstone (Plate 25), Zone B Sandstone (Plate 27), and the Riceville Shale (Plate 39).

Figure 8 illustrates some of the more interesting structural and stratigraphic features associated with this Greene-Potter zone. The three major radioactive shale facies, Marcellus, Rhinestreet, and Dunkirk, form three broad belts in western Pennsylvania (Figure 8A). The Marcellus attains its greatest

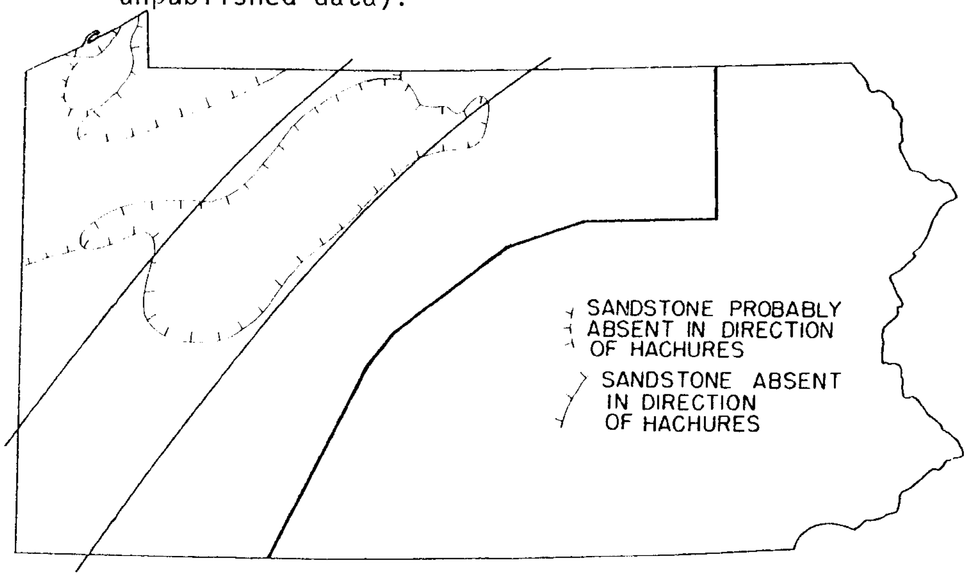
A. Distribution of the three major radioactive shale facies.



B. Location of postulated Late Cambrian growth faults of Wagner (1976).



C. Areas of known and speculated absence of Oriskany Sandstone (after Jones and Cate, 1957, and Heyman, unpublished data).



D. Distribution of shallow oil and gas fields in Pennsylvania (from Lytle and Balogh, 1977).

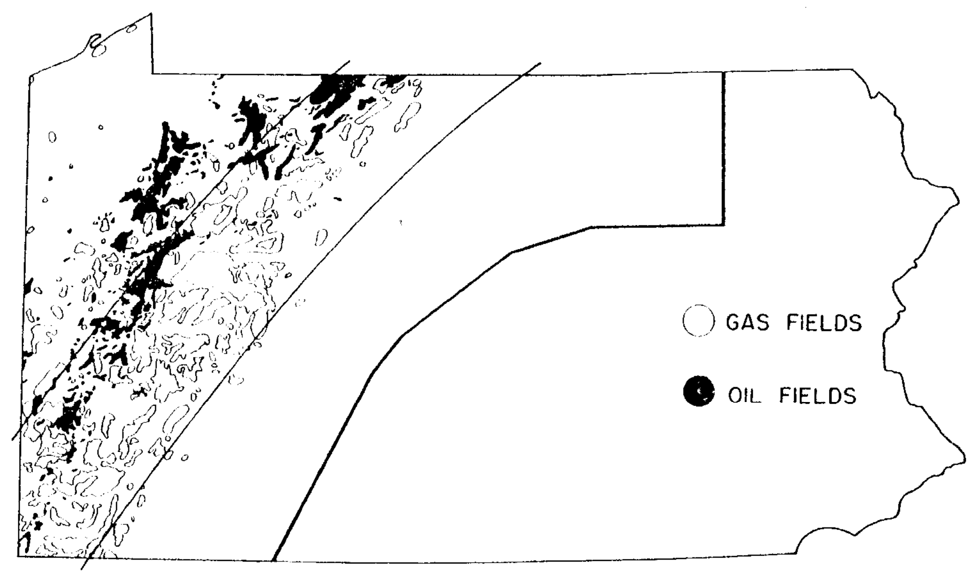


Figure 8. Distribution of various structural and stratigraphic features in the subsurface of Pennsylvania and their relationship to the Greene-Potter zone (bounded by heavy lines).

thickness east of the Greene-Potter zone while the Rhinestreet and Dunkirk are best developed to the west. The postulated Cambrian and Ordovician growth faults of Wagner (1976) lie along the margins of the zone (Figure 8B). Distribution of the sands of the Oriskany Group appear to be related as well (Figure 8C) being absent in the area of the Greene-Potter zone. Distribution of the shallow Devonian oil and gas fields (Figure 8D) is probably also influenced by this phenomenon, either directly or indirectly. Other published data indicate similar relationships throughout geologic time (e.g. reef trends reported by Piotrowski, 1976a and 1976b, in the Onondaga Group in McKean County).

Woodward (1961) seems to be the first to have noticed structural trends of this sort in the subsurface. He proposed a Lower Cambrian "coastal declivity" in western West Virginia that may have continued northeast into Pennsylvania. Wagner (1976) postulated a series of Late Cambrian and Ordovician growth faults which delineated a Late Cambrian trough called the Olin Basin. The axis of the Olin Basin approximately coincides with the axis of the Greene-Potter zone. Harris (1978) referred this zone to the northern portion of the Eastern Interior Aulacogen which includes the Rome Trough of Kentucky and West Virginia. Root (personal cummunication, 1978) suggests numerous data supporting the existence of a proposed Greene-Potter fault zone, including some of the evidence presented here. We feel that use of the term fault zone is premature as there is no substantiated evidence of faulting within the zone.

It is not our objective to attempt to explain the Greene-Potter zone. We simply point out that the distribution of facies, and net feet thicknesses of those facies, appear to bear some relationship to the zone. This phenomenon requires further study and detail before any hypotheses can be made concerning its origins and its relationship to structural and stratigraphic features in the geologic record.

SUMMARY

1. The Devonian organic-rich, radioactive, black shales of Pennsylvania are known producing reservoirs of natural gas (and to a limited extent, oil) which have been exploited in the past. Only recently has interest been renewed in these shales.

2. It has been shown by several workers that an empirical relationship exists between high gamma ray response on a geophysical log and gas production from shales. High gamma ray response is probably a result of concentration of uranium in the organic matter of black shales.

3. The relatively greater production of natural gas from the Dunkirk radioactive shale facies than from the Rhinestreet and Marcellus facies is a direct result of extensive natural fractures of the rock in the area of Dunkirk shale distribution (Erie and Crawford Counties). Exploration and production have been economically more feasible with regard to the Dunkirk because of shallower drilling depths.

4. Three major black shale facies exist in the subsurface of Pennsylvania: (1) the Marcellus facies of the Hamilton Group, (2) the Rhinestreet facies of the West Falls Formation, and (3) the Dunkirk facies of the "Canadaway Group".

5. The Upper Devonian sandstone oil and gas reservoirs are divided into three zones representing "bundles" of sandstone lenses which are distributed in bar and channel patterns. These zones, which are intercalated with zones of shale, represent three progradational phases of the Devonian clastic wedge with each zone extending farther to the northwest than the preceeding one.

6. The three major radioactive shale facies are distributed in northeast-southwest striking belts which may be related to a zone lacking significant radioactive shale thickness extending from Greene County to McKean and Potter Counties (the suggested Greene-Potter fault zone of Root). The Marcellus is most well developed east of this zone, and the Rhinestreet and Dunkirk are

confined to the west of it.

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